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Optimum for the Gasdynamic System in a Fast-Axial-Flow CO_2 Laser

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Abstract: It is reported that the temperature rise of the discharge mixture, in a fast-axial-flow CO_2 laser, can be decreased by increasing both the mass flow rate and the speed of the mixture through the laser tube. However, increasing the mixture speed, in a practical gasdynamic system, will lead to decreasing the mass flow rate, and thus the discharge tube with appropriate cross section, which matches the properties of the given blower driving the mixture to flow, should be chosen to obtain the optimal operation of the laser.

I. Introduction

In a CO_2 laser the fast flow of gas is intended to cool down, through fast convection current, the waste heat generated by discharging so that the laser device would be maintained at a low temperature and to ensure smooth operation. Therefore, the function of the gasdynamic system can significantly affect the performance of laser output. Especially for a fast-axial-flow CO_2 laser, high-pressure high-speed fans are used in order to have

good laser output.

Generally, the bigger the capacity of exhaust fan the better it is for the operation of laser. However, flow resistance exists in an actual gasdynamic system and pressure loss is inevitable, resulting in degradation of the actual capacity of the fan. Particularly in cases where the structure of the flow channel is inadequate, one can not be too optimistic about the actual gas flow even though the rated capacity of the fan may be quite impressive. Furthermore, bigger volume is usually associated with bigger capacity of the fan and the structure of the gasdymanic system of a laser is enlarged, along with the higher operating cost. As a result, optimization of the structure of gasdynamic system is necessary to allow full advantage of the high speed of the fan and to obtain adequate laser output from as small a fan as possible.

For fast-axial-flow CO_2 lasers, the flow resistance mainly /53
comes from the discharging tube. The result of this study shows that optimum output characteristics can be obtained by choosing discharging tubes with dimensions adequately compatible with the function of the exhaust fan.

II. Factors affecting gas temperature rise

In any CO_2 laser media, the particle inversion density between the upper and lower laser energy levels drops quickly with the rise in gas temperature.[4] With other conditions unchanged, the lower the gas temperature the better the laser

power output.[4,5] Therefore, major factors affecting rise in gas temperature should be known when fast-axial-flow CO_2 laser is developed. For this reason we used a first-order approximation equation for energy:[1]

$$\rho u \frac{\partial}{\partial x}\left(C_p T + \frac{1}{2}u^2\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) + G \qquad (1)$$

with special consideration for fast-axial-flow CO_2 laser. When the gas speed is increased the flow field distribution follows the turbulent flow distribution[2]. The electron density distribution for turbulent flow discharging[3] was coupled into equation (1). After numerical calculation and analysis, we obtained the gas temperature increase as a function of gas mass flow (see figure 1) and also the dependence of gas temperature increase on gas flow speed. In other words, when the input power is fixed, gas mass flow and gas speed both affect gas temperature independently. Figure 2 shows the dependence of gas temperature increase on gas flow speed.

The idea to independently use gas mass flow and gas speed to study rise in gas temperature was based on the following thought experiment: Assuming that the gasdynamic system of the experiment device consists of a continuously adjustable fan and a discharging tube with variable cross section. When the mass flow of the system was constant, the gas flow speed can be changed by changing the cross sectional area of the discharging tube and adjusting the fan speed so that gas mass flow was not changed.

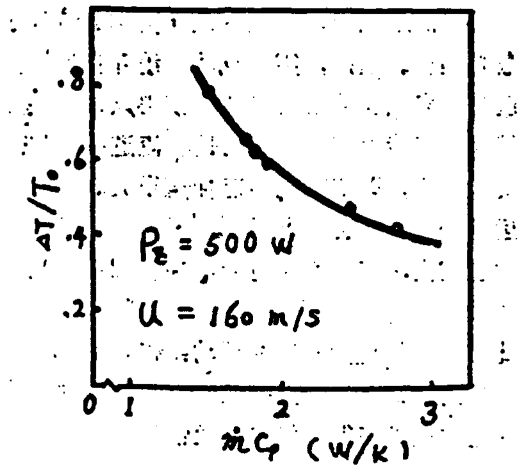

Figure 1: Relationship between temperature rise ΔT and mass flow m

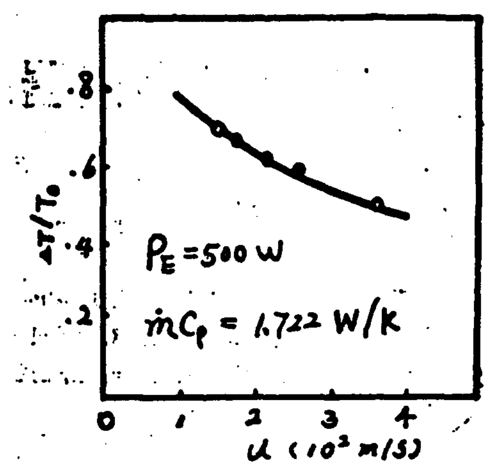

Figure 2: Relationship between temperature rise ΔT and gas speed

When it is desired to change gas mass flow while holding gas speed constant, the fan speed can be changed when the cross sectional area is adjusted at the same time. This experiment proves that it is practical to treat gas speed and gas mass flow

as two independent variables when rise in gas temperature is studied.

Figure 1 shows that when discharging power and gas speed are both held constant the rise in temperature of discharged gas decreases with the increase in gas mass flow. Figure 2 shows that when discharging power and gas mass flow are held constant, the rise in temperature of discharged gas decreases with increase in gas speed. Therefore, increase in mass flow and gas speed are beneficial to operation of laser devices. As a consequence, a high speed fan with excellent function is important to a laser system. However, after a fan is chosen, is it still possible to increase gas speed and at the same time guarantee the rated speed? This is the gasdynamic problem we are going to discuss.

III. Characteristics of Practical Gasdynamic Systems

For a practical system with a chosen fan, the gas mass flow
m through discharging tube will not exceed the rated speed of the /54
fan. The gas speed entering the discharging tube u will change as the cross sectional area A changes. How will mass flow m be affected when A is changed? To answer this question, we have carried out a series of observations on a HF-500 fast-axial-flow CO_2 laser.

1. For a fixed system, gas speed u and mass flow m are affected by cross sectional area A through the dynamic pressure P_d and static pressure P_s as:[2]

$$P_a = \frac{1}{2}\rho u^2 \tag{2}$$

where ρ is the gas flow density and can be expressed as:

$$\rho = \frac{273.16}{760} \cdot \frac{M}{V_0} \cdot \frac{R_s}{T} \tag{3}$$

where M and V_0 are the molar mass and molar volume of the gas, respectively, and T is the gas temperature. The mass flow can be expressed as:

$$\dot{m} = u \cdot A \cdot \rho \tag{4}$$

Therefore, the variation of m and u as a function of A can be obtained as long as the dynamic pressure P_a, static pressure P_s, and gas temperature T are measured for various cross sectional area of the discharging tube.

In reality, m is proportional to gas flow Q (torr l/s) and Q is proportional to the actual volume speed Q_c(l/s) of the fan. We would only discuss the relationship between Q_c and A.

In a system, gas flow Q satisfies a continuous equation as:

$$Q = P_s \cdot u \cdot A \tag{5}$$

and therefore Q_c can be expressed as:

$$Q_c = Q/P_s' = u \cdot A \cdot P_s/P_s' \tag{6}$$

where P_s'is the static pressure at the inlet of the fan. Therefore, Q_c can be obtained by measuring the pressure.

For various cross sectional areas, P_a, P_s, P_s' and T were

measured and equations (2), (3), and (6) were used to obtain u and Q_c as functions of A. The functional relationship is shown in figure 3.

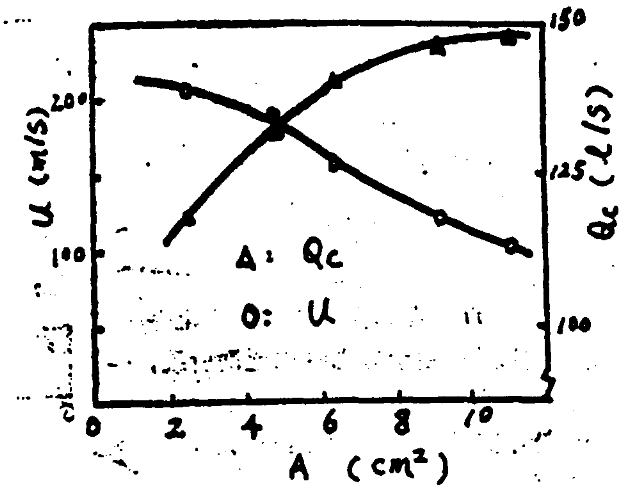

Figure 3: Dependence of gas speed u and fan speed Q_c on cross sectional area A of discharging tube

Figure 3 shows that in an actual system, when the cross sectional area is changed to increase gas flow speed, the actual speed of the fan will be decreased and increase in gas mass flow and gas speed can not be obtained at the same time. In other words, increase gas speed by decreasing cross sectional area is obtained by sacrificing gas mass flow.

2. The reason Q_c is decreased is because when the cross sectional area of the discharging tube is changed, the structure of the gas channel is changed, resulting in change in flow guidance and static pressure P_s' and P_s'' at the outlet. Experimental results have shown that for an identical discharging tube, the pressure difference $\Delta P_s = P_s' - P_s''$ increases with the

increase in the system pressure P while the pressure ratio $\zeta = P_s''/P_s'$ does not change with P. Hence, ζ truly reflects the structural characteristics of the actual system. Figure 4 shows the measurement results. It indicates that Q_c decreases rapidly with the increase in ζ. /55

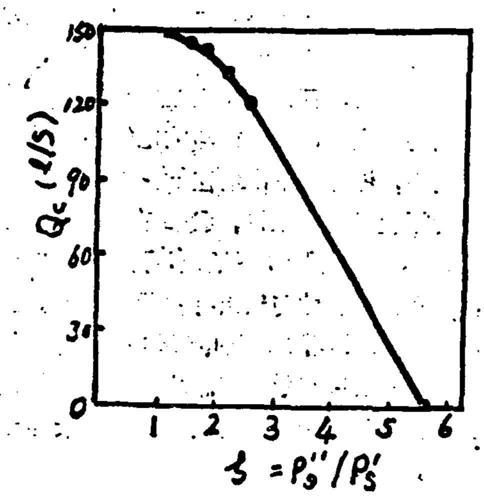

Figure 4: Effect of pressure ratio ζ on fan speed Q_c

In reality, when the cross sectional area of the discharging tube is decreased, the resistance of the gas flow is increased and pressure head loss is increased, resulting in increase in outlet/inlet pressure ratio ζ and increase in loss of the fan and decrease in actual speed of the fan. This observation reminds us that in the design of fast-axial-flow CO_2 laser systems, the loss at regions not related to discharging tube should be reduced as much as possible in order to improve the performance of the laser system.

3. The decrease in mass flow m is inevitable. The above analysis shows that decrease in Q_c is due to loss of fan. Therefore, can the mass flow be kept unchanged if the fan has excellent quality and the loss was kept at a minimum? In order to illustrate this problem, equation (6) was modified as:

$$Q = Q_C \cdot P_s' \qquad (7)$$

When the cross sectional area of the discharging tube is reduced, the pressure loss of the flow duct is increased and P_s' would decrease with decrease in A. Therefore, from equation (7) it is clear that even if Q_c is kept unchanged Q would still be decreased. Therefore, no matter how well the fan would perform, when the cross sectional area of the discharging tube is decreased, the gas mass flow through the discharging tube would be decreased.

IV. Optimal Operation Condition

Because in a fast-axial-flow CO_2 laser the rise in discharged gas is determined by gas mass flow and gas speed, and it is not possible to obtain high speed and high mass flow at the same time, it is impossible to expect identical result from gasdynamic structures with different dimensions of the discharging tube. Hence, for a given fan, there exists a discharging tube with dimensions best suit the gasdynamic structure of the system and would guarantee the best laser output.

In order to provide evidence for the principle outlined above, temperature rise and laser output characteristics on a HF-500 fast-axial-flow CO_2 laser with discharging tubes with various cross sectional areas were measured and shown in figure 5. It is obvious that with the increase in A there exists a minimum value for temperature rise and a maximum in output power. This also explains the fact that there exists a optimal gasdynamic structure which will guarantee optimal laser output.

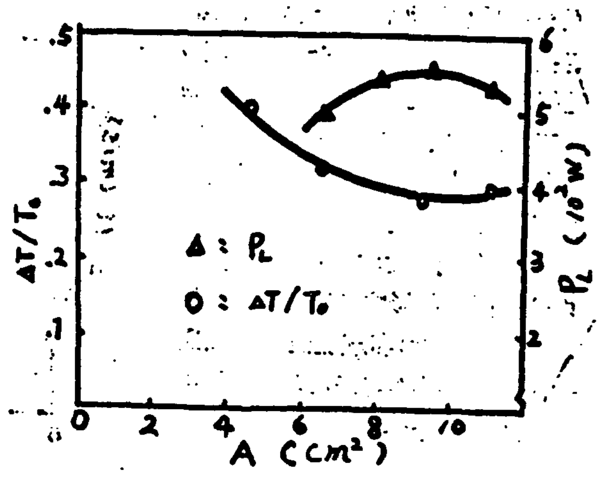

Figure 5: Illustration of a maximum in output power and a minimum in temperature rise as the cross sectional area of the discharging tube is increased.

V. Conclusions

For a fast-axial-flow CO_2 laser system, rise in discharged gas is determined by gas mass flow and gas speed. For a gasdynamic system with selected fan, gas speed is mainly determined by the dimension of discharging tube and increase in

gas speed will result in decrease in mass flow. Therefore, choice of dimension of the discharging tube should consider effects on both m and u so that the gasdynamic system can be maintained at an optimal working condition. Experimental results have shown that laser output characteristics can be improved when a discharging tube matching the fan is selected.

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